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# Integrated assessment of climate and human contributions to variations in streamflow in the Ten Great Gullies Basin of the Upper Yellow River, China

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**Abstract:** Climate change and human activity are two linked factors that alter the spatiotemporal distribution of the available water. Assessing the relative contribution of the two factors on runoff changes can help the planners and managers to better formulate strategies and policies regarding regional water resources. In this work, using two typical sub-basins of the Yellow River as the study area, we first detected the trend and the breakpoint in the annual streamflow data with the Pettitt test during the period 1964–2011. Next, a Budyko-based climate elasticity model and a monthly hydrological model were employed as an integrated method to distinguish the relative contributions of climate change and human activities to the long-term changes in runoff. The results showed that a significant decline in the annual runoff occurred in the two sub-basins during the study period, and the abrupt change point in the annual runoff at the two sub-basins both occurred in 1997. The conceptual hydrological model performed well in reproducing monthly runoff time series at the two sub-basins. The Nash-Sutcliffe efficiency (NSE) between observed and simulated runoff during the validation period exceeds 0.83 for the two sub-basins. Climate elasticity method and hydrological model give consistent attribution results: human activities are the major drivers responsible for the decreased annual runoff in the Ten Great Gullies Basin. The relative contributions of climate change and human activities to the changes in the annual runoff were 22–32% and 68–78%, respectively.

**Keywords:** Climate variability; Human activity; Quantitative method; Streamflow change; Ten Great Gullies Basin.

## 1 INTRODUCTION

Freshwater is a scarce resource in many regions of the world, and it is essential for many aspects of the environment, economy, and society (Campbell et al., 2011). Changes in water resources have an important impact on the sustainable development of human society, including infrastructure construction, economic growth, drought protection, flood control, energy consumption, and food security. Climate variability and human activities are considered as the two main factors responsible for changes in water availability (Bao et al., 2012). Climate change directly alters the meteorological variables that affect the spatiotemporal variations in water availability, such as precipitation, temperature, and wind speed. Human activities can also affect terrestrial hydrological processes through changing land-use such as soil and water conservation, urban construction, and deforestation (Brown et al., 2005; Ma et al., 2010; Nagy et al., 2012). Hence, understanding the relative contributions of climate change and human activities to runoff changes is increasingly important for the management of water resources (Lakshmi et al., 2011).

A general approach to separate the relative contributions of climate change and human to runoff changes is to divide the runoff time series into two periods: the "baseline or natural period" and the "impacted period", based on abrupt change tests (Obeysekera et al., 2011; Pekarova et al., 2006). In the "baseline period", change in runoff is mainly attributed to climate change, and the influence of human activities is negligible. In the "impacted period", change in runoff is considered as the result of the combined effects of climate change and human activities. Using the model parameters calibrated from the "baseline period" and forcing data during the "impacted period", the assessment models can simulate the natural runoff time series that only reflects the influences of climate change. The difference between the modeled and observed runoff during the "impacted period" can be attributed to the factors other than climate change, that is, human interferences (Wang and Hejazi, 2011; Zhao et al., 2015). The commonly used assessment models include the process-based hydrologic models and statistics-based methods (Huang et al., 2016; Zhang et al., 2014). For examples, Liang et al. (2013) employed the simple lumped conceptual daily rainfall-runoff (SIMHYD) model to evaluate the impacts of changes in plantations and climate variability on annual runoff in the Kuye River. Zhang et al. (2012) used the soil and water assessment tool (SWAT) to estimate runoff changes under the impacts of climate change and human activities in the Huifa River Basin. Xu et al. (2013) quantified the cause of the annual runoff change in the Luan River Basin by using the geomorphology-based hydrological model (GBHM). Despite hydrological models are powerful tools for attribution analysis regarding runoff changes, some uncertainties inevitably exist in hydrological models. Statistical methods can be served as a supplement to hydrological models to detect runoff responses to various disturbances, especially in regions where long-term historical hydrometeorology data are available (Roudier et al., 2014; Zhang et al., 2012). Among the various statistical methods, the Budyko-based climate elasticity method has been widely used around the worldwide (Mwangi et al., 2016; Roderick and Farquhar, 2011; Ye et al., 2013). This method is a simple but effective tool to attribute runoff changes at mean annual time scales (Liu et al., 2009; Ma et al., 2010; Roderick and Farquhar, 2011; Schaake and Waggoner, 1990; Wang et al., 2013).

The Ten Great Gullies is a subbasin of the upper reach of the Yellow River and located in the northern Ordos Plateau, Inner Mongolia, China. This area is one of the areas with the most serious soil erosion in the Yellow River basin. Historically, the high-sand floods during the rainy season often block the Yellow River, causing dikes to burst and flooding the Hetao plain. To alleviate soil erosion, a series of ecological restoration measures have been implemented in this region since 1950s (She et al., 2014). Particularly for the “Grain-for-Green Project”, which was implemented as a large reforestation campaign in 1999 in order to return cultivated lands with slopes greater than 15° to forests and grasslands (Zhang et al., 2012). In addition to intense human activities, the climate in this region has become warmer and drier over the past several decades. Under the combined effect of climate change and human activities, the annual runoff of many river basins in the middle reaches of the Yellow River has shown a decreasing trend (Chang et al., 2015). Previous studies have reported a reduction in annual runoff in this region (Li et al., 2019; Ran et al., 2015), but the dominant factor responsible for the reduced runoff in this basin remains unclear. In addition, previous studies generally used a single method to distinguish the effects of climate change and human activities on runoff changes, lacking of mutual verification between different methods for assessment results (Gao et al., 2016; Ye et al., 2013; Zhang et al., 2016; Zuo et al., 2014).

In the present study, we employed an integrated approach consisting of Budyko-based climate elasticity method and a monthly hydrologic model to quantify the relative contributions of climate change and human activities to runoff reduction in the study area. The main objectives of the present study were: (1) to detect the statistical trend and abrupt change in annual runoff time series; (2) to quantify the relative contributions of climate variability and human activities to runoff reduction, and (3) to analyze the specific water conservation measure that significantly reduces annual runoff. This work highlights that the negative effect of soil and water conservation measures on water yield in water-limited regions.

## 2 STUDY AREA AND DATA

### 2.1 Study area

The Ten Great Gullies is a typical region in the desert region of the eastern Ordos Plateau and the rivers in this area flow through the Hobq Desert and across the lower alluvial plain before finally entering the Yellow River. The drainage area is approximately 11,000 km$^2$ and it includes (from west to east) the Maobula, Buersetaigou, Heilaigou, Xiliugou, Hantaichuan, Haoqinghe, Hashilachuan, Muhaerhe, Dongliugou, and Husitaihe tributaries. The study area has a population of 158,000. The landform has band-shaped distribution features and can be divided into three types: a hilly and gully area, desert area, and alluvial plain area. Chestnut and sandy soil is widely distributed in different regions as the dominant soil type. The region has a temperate continental monsoon climate with potential evapotranspiration (ET$_0$) of 2800 mm, and the mean annual temperature is 6.1°C. The mean annual precipitation ranges from 300 to 400 mm, and the rainy season is concentrated between July to September. Strong winds and sandstorms occur often in the winter and spring, with frequencies of 25.2 and 19.7 days per year, respectively (YRIHR, 2009). Large amounts of eolian sediment can be deposited and stored temporarily in the river channel during windy seasons, which may be transported downstream by floods propagating into the Yellow River during the following rainy season.

Due to the special geographical location and natural environment, this region has become the main source of the sediment delivered to the Inner Mongolian Reach, which commonly accumulates in the confluence and blocks the flow of the river, thereby causing the collapse of dikes, severe channel deposition, and riverbed elevation (Feng and Zhang, 2008; Zhao et al., 2001). The study area has two hydrometric stations at Longtouguai and Xiangshawan, which are located in the Xiliugou and Hantaichuan gullies, respectively (Figure 1).

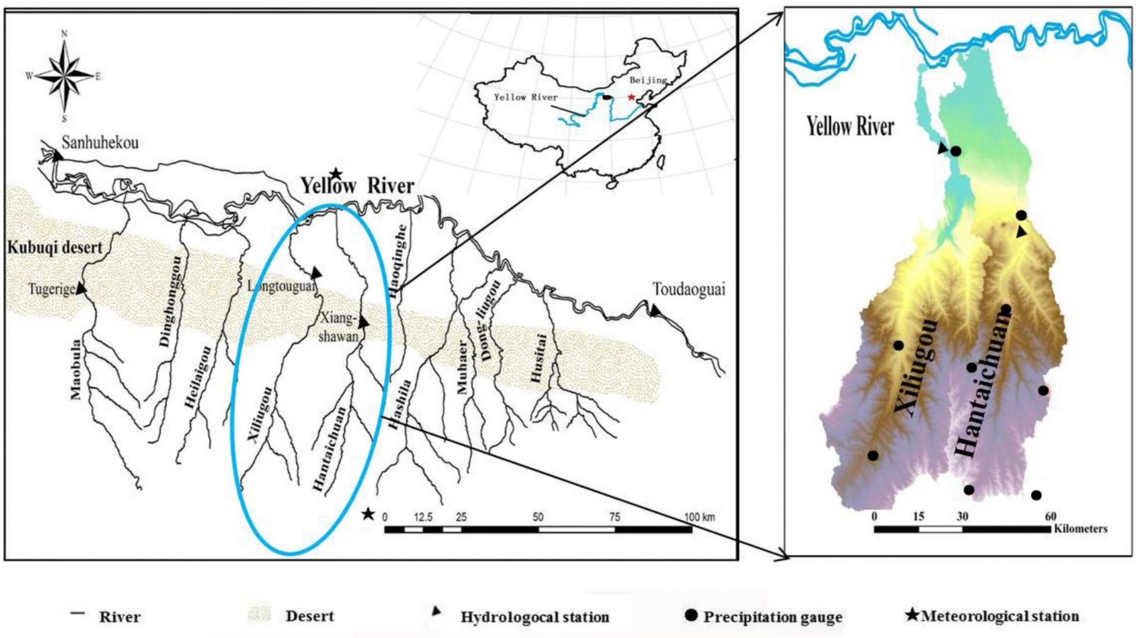


**Fig. 1.** Map of the study area.

### 2.2 Data

Monthly natural streamflow data from two hydrological stations were extracted from the Hydrological Bulletin of the Yellow River Basin, which is issued annually by the Yellow River Conservancy Commission. Natural streamflow data refer to the sum of discharge observations recorded from stream gauge stations and the amount of water used by human beings. Daily precipitation records from nine precipitation stations and two weather stations were used in this study (Figure 1), covering the period 1964–2011. Precipitation data from nine rainfall gauges in the region were also provided by the Erdos Hydrological Bureau of Inner Mongolia. Wind speed, temperature, actual vapor pressure, and sunshine duration data were obtained from the National Climate Center of the China Meteorological Administration (CMA). These data were used to calculate $ET_0$ using the FAO Penman–Monteith method described in FAO-56 (Allen et al., 1998). The average of the meteorological data from the two weather stations was applied to the two sub-basins. Land use/cover maps of the watershed in 1990 and 2010 were interpreted from Landsat TM images at a spatial resolution of 30 m. The data sets were downloaded from the Data Sharing Infrastructure of Earth System Science of the Chinese Academy of Sciences (http://www.geodata.cn/Portal/dataCatalog/dataList.jsp), and image processing was performed using ERDAS Imagine 9.2 (ERDAS, Inc., Norcross, Georgia) in order to classify the land cover into seven categories by supervised classification and artificial visual interpretation. The land use types in 2010 were tested and verified based on 48 actual ground control points captured with GPS equipment for all land use types. The overall accuracy of land classification was approximately 84% and the kappa statistic was 0.77, which indicated that the land use/cover data interpreted from the images were suitable for use in this study (Ma et al., 2009).

## 3 METHODOLOGY

### 3.1 The change point detection

The Pettitt test (Pettitt, 1979) is used to test one unknown change point by considering a sequence of random variables, i.e., $X_1$, $X_2 \dots X_t$, that has a change point at $\tau$ ($X_t$, where $t$ = 1, 2, …, $\tau$, has a common distribution function $F_1(x)$; $X_t$, where $t = \tau + 1$, …, $T$, has a common distribution function $F_2(x)$; and $F_1(x) \neq F_2(x)$) (Pettitt, 1979). The null hypothesis $H_0$ (no change or $\tau = T$) is tested against the alternative hypothesis $H_a$ (change or $1 \le \tau < T$) using the non-parametric statistic:

$$K_N = \mathrm{Max}_{1 \le t \le T} \left| U_{t,T} \right| \tag{1}$$

where the test used a version of the Mann-Whitney statistic $U_{t,T}$

$$U_{t,T} = U_{t-1,T} + \sum_{i=1}^{T} \mathrm{sgn}(X_t - X_i) \qquad t = 2, 3, \dots\dots, T \tag{2}$$

and

$$\mathrm{sgn}(X_t - X_i)\begin{cases} 1 & X_t - X_i > 0 \\ 0 & X_t - X_i = 0 \\ -1 & X_t - X_i < 0 \end{cases} \tag{3}$$

The associated probability, $P$, used in the test is given as follows:

$$P = 2\exp\left( \frac{-6K_N^2}{N^3 + N^2} \right) \tag{4}$$

If $P < 0.05$, a significant change point exists, and the time series is divided into two parts at the location of the change point.

### 3.2 Climate elasticity method

The Budyko-based climate elasticity method is an effective tool for separating the impacts of climate change and human activities on runoff change. According to the Budyko hypothesis, this approach describes the annual water balance primarily as a function of water availability (precipitation) and energy availability (potential evapotranspiration) (Budyko, 1974). For a given catchment, the total variation in the observed mean annual runoff ($\Delta\overline{Q}$) before (natural period) and after (impacted period) the change point could be caused by a combination of climate variability ($\Delta\overline{Q_C}$) and human activities ($\Delta\overline{Q_H}$) (Li et al., 2007) as follows.

$$\Delta\overline{Q} = \Delta\overline{Q_H} + \Delta\overline{Q_C} \tag{5}$$

The long-term water balance in a given basin is primarily controlled by the water availability (precipitation) and energy availability ($ET_0$) (Dooge et al., 1999). Assuming that the water storage on the mean annual scale is zero, the influence of climate variability on the mean annual runoff can be estimated using the following formula (Dooge et al., 1999; Milly and Dunne, 2002):

$$\Delta\overline{Q_C} = \Delta\overline{Q_P} + \Delta\overline{Q_{E_0}} = (\varepsilon_P \frac{\Delta P}{P} + \varepsilon_{E_0} \frac{\Delta E_0}{E_0})Q \tag{6}$$

where $\Delta\overline{Q_C}$, $\Delta\overline{Q_P}$, and $\Delta\overline{Q_{E_0}}$ denote the changes in the natural streamflow, precipitation, and $ET_0$, respectively, and $\Delta P$ and $\Delta E_0$ represent the variation in the annual precipitation and $ET_0$ before and after the change point. The coefficients of the sensitivities of the streamflow to precipitation ($\varepsilon_P$) and $ET_0$ ($\varepsilon_{E_0}$) can be determined as follows:

$$\varepsilon_P = 1 + \frac{\varphi F'(\varphi)}{1 - F(\varphi)}, \ \varepsilon_P + \varepsilon_{E_0} = 1 \tag{7}$$

where $\varphi$ is a function of the average aridity index, which can be calculated as the ratio of the mean annual $ET_0$ relative to the mean annual precipitation ($ET_0$/P), $F(\varphi)$ is a function used to partition the mean annual P into runoff and actual evapotranspiration (ET), and $F'(\varphi)$ is the derived function of $F(\varphi)$. Various mathematical equations have been developed for $F(\varphi)$ based on the Budyko hypothesis, and a detailed review of these equations was provided by Zhang et al. (2001). In the present study, the following expressions are used:

$$\begin{cases} F(\varphi) = (1 + \omega\varphi) / (1 + \omega\varphi + 1/\varphi) \\ F'(\varphi) = (\varphi^{-2} + 2\omega\varphi^{-1} + \omega - 1) / (1 + \omega\varphi + 1/\varphi)^2 \end{cases} \tag{8}$$

where $\omega$ is a plant-available water coefficient that reflects the transpiration process for soil water in arid and humid regions

(Zhang et al., 2001). Assuming that the changes in water storage can be ignored at the annual scale, the parameter $\omega$ is calibrated by minimizing the absolute error between the water balance-based (precipitation minus runoff) and simulated ET at the annual scale.

### 3.3 The conceptual hydrological model

Physically-based models have long been considered as the gold standard for runoff simulations as they account for the spatial heterogeneity of climatic and landscape factors. However, for most studies on the impact of climate change and human activities on runoff changes, they tend to choose the conceptual hydrological models due to the following three reasons. First, physically-based models often require a variety of climate and landscape data as inputs, and data preparation is time-consuming and laborious. Second, physically-based models usually contain a large number of parameters, and thus the parameter calibration is time-consuming. By contrast, conceptual models generally require minimal inputs and parameters and can provide similar or even better runoff simulations than physically-based models (Bai et al., 2015; Li et al., 2011). Here, a monthly conceptual model called the dynamic water balance model (DWBM) was employed as an alternative approach to separate the relative contributions of climate change and human activities to the runoff changes. This model has been used widely for simulating and predicting monthly runoff under different climate conditions globally (Bai et al., 2015; Li et al., 2011; Li et al., 2016; Zhang et al., 2017; Zhao et al., 2017). The DWBM was developed by extending the Budyko framework, or the concept of "limits and controls'' (Wang et al., 2011). This is a lumped conceptual model with two stores comprising the soil root zone store and groundwater store (Figure 2). The model structure of the DWBM has two advantages. First, the evapotranspiration is estimated using a method similar to the Budyko curve. Second, it is assumed that direct runoff and groundwater exchange will also occur even if the soil is not saturated. The precipitation in time step t can be divided into the direct runoff and the sum of the other water balance components:

$$P(t) = Q_d(t) + X(t) \tag{9}$$

where $X(t)$ is the catchment rainfall retention, which is the amount of rainfall retained by the catchment for evapotranspiration $ET(t)$. The catchment rainfall retention $X(t)$ can be calculated as:

$$X(t) = P(t)F\left(\frac{X_0(t)}{P(t)}, \alpha_1\right) \tag{10}$$

where $F(\ )$ is a partitioning function based on the Budyko concept, $\alpha_1$ is the retention efficiency, i.e., a larger value of $\alpha_1$ will result in more rainfall retention and less direct runoff, and $X_0(t)$ is the potential evaporation.

The direct runoff is calculated based on Equations (9) and (10) as follows.

$$Q_d(t) = P(t) - X(t) \tag{11}$$

At sub-annual time scales, the water availability $W(t)$ can be defined as:

$$W(t) = X(t) + S(t-1) \tag{12}$$

Together with the definition of $X(t)$, we obtain:

$$W(t) = ET(t) + S(t) + R(t) \tag{13}$$

Equation (13) defines the source of water availability. Equation (14) determines the partitioning expressed as

$$W(t) = Y(t) + R(t) \tag{14}$$

Then, $Y(t)$ is the evapotranspiration opportunity and it can be estimated as

$$Y(t) = W(t)F\left(\frac{E_0(t) + S_{\max}}{W(t)}, \alpha_2\right) \tag{15}$$

where $\alpha_2$ is a model parameter representing the actual evapotranspiration efficiency coefficient. $ET(t)$ can be affected by the potential evapotranspiration $E_0(t)$ and the available water $W(t)$. Similar to Budyko (1958), the evapotranspiration $ET(t)$ can be calculated as:

$$ET(t) = W(t)F\left(\frac{E_0(t)}{W(t)}, \alpha_2\right) \tag{16}$$

The soil water storage can now be calculated as follows.

$$S(t) = Y(t) - ET(t) \tag{17}$$

Finally, the groundwater storage is treated as a linear reservoir, and thus the groundwater balance and baseflow can be modeled as：

$$Q_b(t) = dG(t-1) \tag{18}$$

$$G(t) = (1-d)G(t-1) + R(t) \tag{19}$$

where $Q_b$ is the baseflow, $G$ is the groundwater storage, and $d$ is a constant.

The version used in the present study has four sensitive parameters: retention efficiency ($\alpha_1$), evapotranspiration efficiency ($\alpha_2$), soil water storage capacity ($S_{\max}$), and a baseflow linear recession constant ($d$) (see Figure 2).We calibrated the model parameters using observed runoff during the natural period in each basin. The calibrated model was then used to simulate runoff in the impacted period (1998–2011) with the same parameters as the natural period. The difference between the simulated and observed annual runoff represents the impacts of human activities in the impacted period.

The Nash–Sutcliffe efficiency (NSE) and the relative water balance error percentage (WBE) were used to assess the performance of the DWBM. The two criteria are defined as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2} \tag{20}$$

$$WBE = 100\left(\frac{\sum_{i=1}^{n} Q_{sim,i} - \sum_{i=1}^{n} Q_{Obs,i}}{\sum_{i=1}^{n} Q_{obs,i}}\right) \tag{21}$$

where $Q_{sim,i}$ and $Q_{obs,i}$ denote the simulated and observed streamflow at time $i$, respectively, $\overline{Q_{obs,i}}$ represents the arithmetic mean of the observed streamflow, and $n$ is the number of time steps.

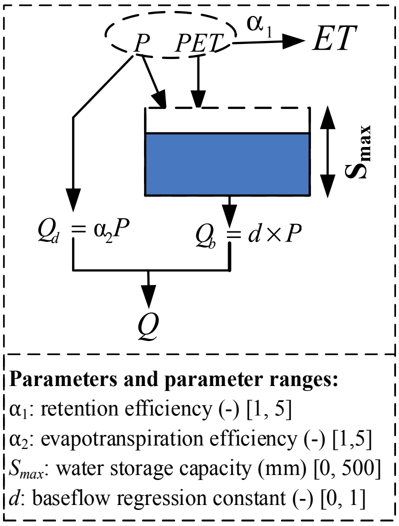


**Fig. 2.** Structure and parameters for the dynamic water balance model (DWBM).

## 4 RESULTS

### 4.1 Change in the annual runoff and climate factors

The abrupt changes of annual runoff detected by the Pettitt test are shown in Figure 3 and Table 1. The abrupt change of annual runoff in the two sub-basins both occurred in 1997 ($P < 0.05$), and thus the sub-periods before and after 1997 are identified as the "natural period" (period I: 1964–1997) and "impacted period" (period II: 1997–2011). The observed average annual runoff in the Xiliugou basin was 27.4 mm/yr in the period I and 18.3 mm/yr in the period II, respectively; the value of the two periods in the Hantaichuan basin was 12.8 and 7.6 mm/yr, respectively. Compared with period I, the average annual runoff at the Xiliugou and Hantaichuan basins decreased by 9.1 and 5.2 mm/yr, respectively, and the relative changes between the two periods are –33% and –40% (Figure 4a, b).

The average annual precipitation between the periods I and II decreased by 18.9 mm (–6.4%) for the Xilougou basin and for 27 mm (–9.6%) for the Hantaichuan basin. The annual average temperature increased significantly ($P < 0.05$) during the entire study period, with a temperature increase rate of 0.5°C/10a. The warming rate is the most significant in autumn and winter. The annual $ET_0$ in the two basins was approximately 1226.2 mm/yr, and the mean annual $ET_0$ in the period II decreased by 16.6 mm/yr compared with the period I (Figure 4c–e).

### 4.2 Quantitative hydrological responses to climate variability and human activities

#### *4.2.1 Assessment using the climate elasticity method*

The parameter $\omega$ is the only parameter in the climate elasticity method, and its value has a large effect on assessment results (Bai et al., 2020; Chen et al., 2012; Zhang et al., 2001). Here we calibrated the parameter $\omega$ against the water balance-based annual ET estimates (precipitation minus runoff) (Figure 5). The best agreement between the water balance-based and simulated ET occurred when the parameter $\omega$ was equal to 0.70 for the Xilougou basin and 0.67 for the Hantaichuan basin. We then obtained the climate elasticity coefficient of the annual runoff with respect to the precipitation ($\varepsilon_P$) and $ET_0$ ($\varepsilon_{E_0}$) using Eq. (11), and the results are listed in Table 2.

The results showed that a 10% increase in precipitation will increase annual runoff by 12% for the Xilougou basin and 13.5% for the Hantaichuan basin; whereas a 10% increase in $ET_0$ will decrease annual runoff for the two basins by 2.0 and 3.5%, respectively. According to Table 2, the change in precipitation reduced annual runoff by 2.1 mm for the Xilougou basin and 1.7 mm for the Hantaichun basin. Similarly, the change in $ET_0$ caused the annual runoff of both basins to increase by 0.08 mm in the period II. Therefore, the impact of climate change

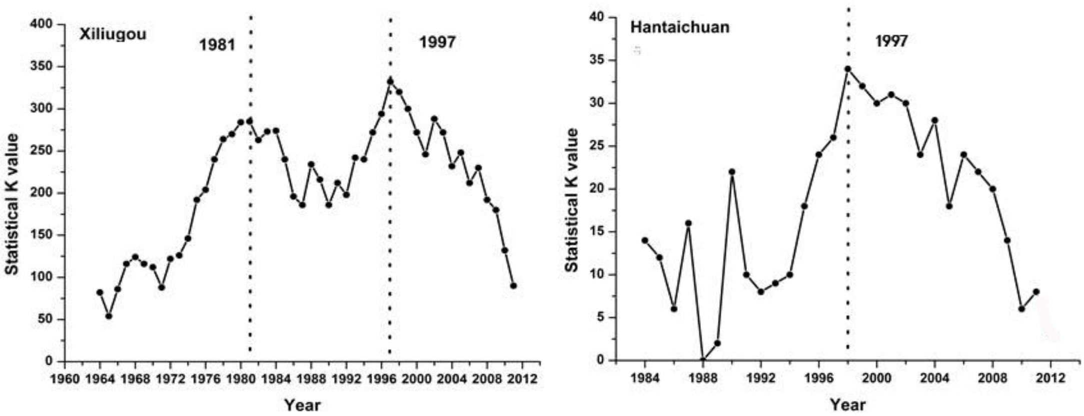


**Fig. 3.** Pettitt test for the annual streamflow in the Xiliugou and Hantaichuan catchments.

**Table 1.** Results of the Pettitt test for streamflow series in two sub-catchments.

| Station | Variable | K statistic | P | Sig level | Shift | T |
|---|---|---|---|---|---|---|
| Xiliugou | streamflow | 234 | 0.065 | ns | – | 1981 |
| | | 282 | 0.014 | * | decrease | 1997 |
| Hantaichuan | streamflow | 35 | 0.747 | ns | – | 1997 |

*Significant at P = 0.05. ** Significant at P = 0.01

**Table 2.** Relative contribution of climate change and human activities on the change in annual runoff estimated from the climate elasticity method.

| Catchment | Natural period (mm) | | | Impacted period | | | Runoff change (mm) | | Proportional change in runoff | |
|---|---|---|---|---|---|---|---|---|---|---|
| | P | $ET_0$ | Q | P | $ET_0$ | Q | $\varepsilon_P$ | $\varepsilon_{E_0}$ | $\Delta Q_C$ (%) | $\Delta Q_H$ (%) |
| Xiliugou | 293.1 | 1231.3 | 27.4 | 274.2 | 1213.8 | 18.3 | 1.20 | –0.20 | 22 | 78 |
| Hantaichuan | 283.0 | 1231.3 | 12.8 | 256.0 | 1213.8 | 7.6 | 1.35 | –0.35 | 32 | 68 |

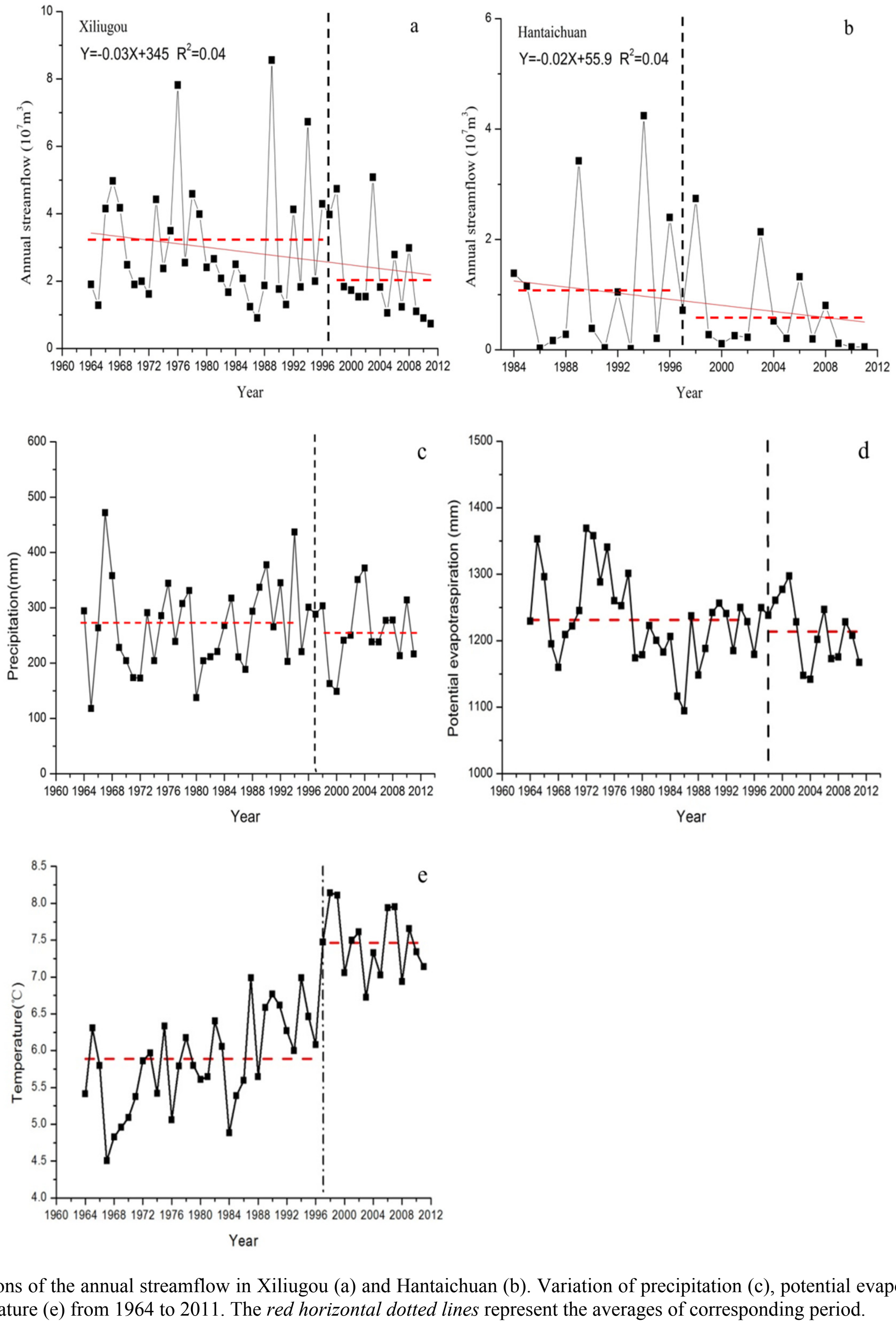


**Fig. 4.** Variations of the annual streamflow in Xiliugou (a) and Hantaichuan (b). Variation of precipitation (c), potential evapotranspiration (d) and temperature (e) from 1964 to 2011. The *red horizontal dotted lines* represent the averages of corresponding period.

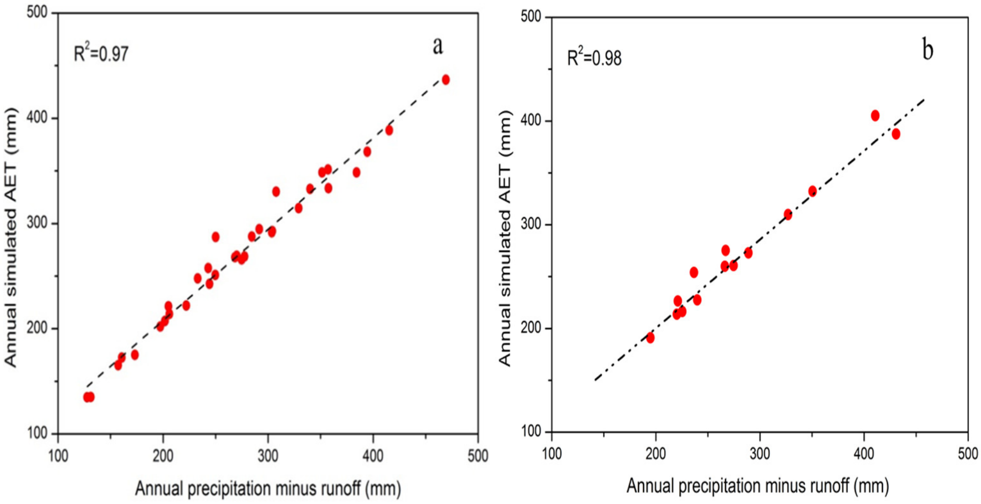


**Fig. 5.** Correlations between the annual actual evapotranspiration (AET) calculated directly from the water balance equation and the AET simulated by Zhang's curve for the "natural period" in Xiliugou (a) and Hantaichuan (b).

has reduced the annual runoff at the Xiliugou and Hantaichuan basins by 2.0 and 1.6 mm, respectively, accounting for 22% and 32% of the decrease in the annual runoff for the two basins. By contrast, human activities were responsible for 78% and 68% of the decreases. Thus, the annual runoff was more sensitive to the change in precipitation than $ET_0$, and the impact of human activities was the primary driver of the decrease in the annual runoff for the two basins.

*4.2.2 Assessment using the hydrological model*

Figure 6 shows the observed and simulated monthly runoff values during the calibration and validation periods and the difference in observed and natural streamflow simulated by DWBM model. The NSE between the observed and simulated runoff at Xiliugou station was 0.84 in the calibration period and 0.85 in the validation period, and the values for Hantaichuan station were 0.80 and 0.83, respectively (Table 3). The WBE values in the validation period were less than 10% at the two stations. These results indicate that the model performed well in simulating the monthly runoff at the two catchments. The difference between the simulated and observed annual runoff after the change point (i.e., period II) was considered to be attributable to human activities. In the Xiliugou catchment, the simulated annual runoff in periods I and II was 23.9 mm and 22.0 mm, respectively, with a decrease of 1.9 mm. In the Hantaichuan catchment, the simulated annual runoff during periods I and II was 14.3 mm and 12.7 mm, respectively, with a decrease of 1.6 mm. Therefore, climate variability accounted for 21% and 31% of the reduction in runoff at Xiliugou and Hantaichuan basins, respectively (see Table 2), whereas human activities contributed 79% and 69% of runoff reduction for the two basins.

## 5 DISCUSSION

### 5.1 Uncertainty sources of assessment results

Despite the two models differ greatly in the attribution principle of runoff change, they showed consistent results on the dominant factor of runoff reduction, thereby indicating that the assessment results were reliable. However, some uncertainties inevitably exist in assessment results. First, the prerequisite of the assessment is that the contributions of climatic and anthropogenic factors are independent of each other. However, the two factors actually interact with each other. Human activities, such as carbon emissions from fossil fuels and land use changes, have a profound impact on the global climate system. In turn, climate change will affect human social behavior and lifestyle. Therefore, it is difficult to completely isolate the effect of one factor on runoff change from another. Second, the length of runoff data used to calibrate the hydrological models may not sufficient to obtain robust parameter estimations. Conceptual hydrological models would suffer from performance degradation when climate conditions between calibration and validation periods are significantly different. Therefore, several studies have suggested that runoff data used for model calibration should include different climatic periods (dry, mixed and wet) to obtained reliable parameter estimates (Bai et al., 2015). Third, the uncertainty may also arise from the model inputs such as precipitation. Zeng et al. (2018) suggested that modeling results tend to stabilize when a drainage basin area is between 605 and 2,148 km$^2$, and the number of rainfall stations is at least 10 to 38. Thus, increasing the number of rainfall stations will increase the accuracy of the simulated flow obtained by a model. Similarly, other studies showed that the density of the rainfall stations may significantly influence the modeling results and that increasing the number of rainfall stations can significantly reduce the uncertainty of the model parameters (Chu et al., 2012; Masih et al., 2011; Shope and Maharjan, 2015). In the present study, only eight rainfall stations and two meteorological stations are available, and the two meteorological stations are located on the periphery of the study basin. Thus, the meteorological inputs of the model cannot fully represent the meteorological conditions in the entire area. Fourth, uncertainty may also stem from the climate elasticity method. This method attributes the natural annual runoff changes completely to P and $ET_0$, whereas other factors may play important roles in regulating the changes in the annual runoff, such as changes in groundwater storage, particularly in dry seasons. Moreover, a part of the variability the model is not explaining may be coming from the misfit to the Budyko-based functional form that is used to partition the mean annual P into evaporation and runoff. Also, the DWBM overestimated the low flow during the natural period in the Huntaichuan basin, and this overestimation probably be propagated to the impact period, thereby exaggerating the effects of human activities on runoff reduction. Nevertheless, the two independent attribution methods consistently indicated that human activities were the primary cause of annual runoff decreases.

**Table 3.** Performance of the DWBM for monthly runoff simulations in the Xiliugou and Hantaichuan catchments.

| Catchment | Period | Year | NSE | WBE |
|---|---|---|---|---|
| Xiliugou | Calibration period | 1964–1981 | 0.84 | –6.4 |
| | Validation period | 1981–1997 | 0.8 | –8.3 |
| Hantaichuan | Calibration period | 1984–1992 | 0.85 | 4.9 |
| | Validation period | 1992–1997 | 0.83 | 1.8 |

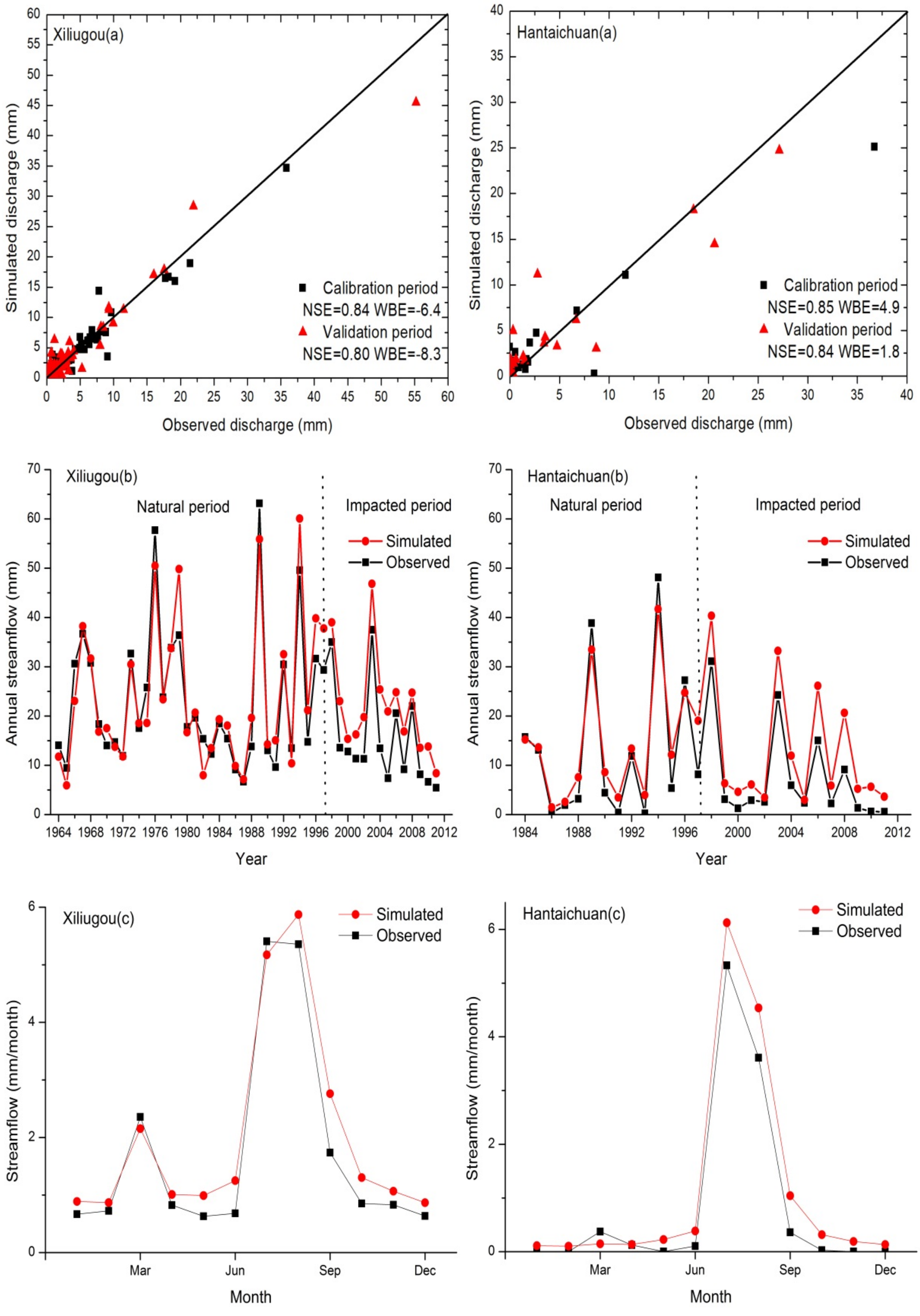


**Fig. 6.** Observed and simulated monthly streamflow in the calibration and validation periods of the two catchments (a). Observed and simulated annual streamflow in the "natural period" and "impacted period" of the two catchments (b). Monthly average observed and simulated streamflow in the two catchments (c).

**Table 4.** Land use change from 1990–2010 in the Xiliugou and Hantaichuan catchments.

| Land use types | 1990 | | 2010 | |
|---|---|---|---|---|
| | Area ($km^2$) | Percentage (%) | Area ($km^2$) | Percentage (%) |
| Cultivated land | 357.9 | 15 % | 296.8 | 12 % |
| Forest | 299.7 | 12 % | 424.8 | 17 % |
| Grass land | 854.5 | 35 % | 1045.1 | 43 % |
| Sand | 420.7 | 17 % | 305.6 | 12 % |
| Water | 134.3 | 5 % | 120.4 | 5 % |
| Resident land | 60.7 | 3 % | 60.3 | 3 % |
| Bare land | 330.5 | 13 % | 205.3 | 8 % |

### 5.2 Human activities

Previous studies have shown that anthropogenic activities were the major causes of the streamflow reductions in the middle Yellow River region during recent decades. For example, Zhou et al. (2013) indicated that human activities accounted for 70% of the runoff reductions in the Wuding River basin, which is one of the large tributaries in the middle of the Yellow River region. In addition, Wang et al. (2012) found that anthropogenic impacts contributed 70% to the streamflow decreases in the Huangfuchuan River basin in the northern part of the middle Yellow River region. Our results also suggested that human activities were the dominant factors responsible for runoff change in the two subbasins. Among a variety of human activities, the land use/cover changes caused by soil conservation measures were regarded as the main factors that led to the runoff reduction in the middle reaches of the Yellow River (Li et al., 2007; Zhao et al., 2015). Table 4 shows the land use changes before and after the “Grain-for-Green Project” being implemented”. It can be seen that the bare land and sandy areas have reduced by 125.1 and 115.1 $km^2$, respectively, from 1990 to 2010, and the reduction in bare and sandy areas were primarily transformed into forests and grassland. The forest area increased by 125.0 $km^2$ and the grassland area increased by 190.6 $km^2$ from 1990 to 2010. In total 315.6 $km^2$ of land was transformed into woodland or grassland, which accounted for 13% of the basin area. This project has significantly increased the vegetation coverage and improved the environmental degradation in the two river basins.

Increased vegetation coverage can lead to larger root water uptake and rainfall interception and then release by evapotranspiration, thereby decreasing the amount of water in the river channels (Zhang et al., 2012). The normalized difference vegetation index (NDVI) is an important indicator to represent the vegetation coverage conditions. Between 1981 and 2011, the NDVI values in Xiliugou and Hantaichuan basins increased by 0.23 (from 0.25 to 0.45) and 0.15 (from 0.25 to 0.4), respectively (Guan et al., 2016). The change in NDVI provides another independent data source to indicate the increased vegetation coverage in the study areas.

Among the various control measures employed, check dams are the main factors responsible for discharge and sediment reductions in the watershed. Between the 1970s and 1990s, there were only two medium-sized check dams in the two basins. However, more than 50 check dams were built in this region between 1997 and 2011 comprising 17 large, 29 medium, and 9 small dams. Due to the important effects of impounding water and the capacity for intercepting sediment transport, these engineering measures significantly affected the high flows by reducing the overland flow and peak streamflow (Xu et al., 2004). The soil and water conservation measures implemented between 1970 and 1996 reduced the water and sediment loads by approximately 0.14 to 0.53 × $10^8$ $m^3$ and 5.4 to 23.6 Mt, respectively (Liang et al., 2015; Zhao et al., 2014).

## 6 CONCLUSIONS

In this study, we separated the relative contributions of climate variability and human activities to the reduction in annual runoff in two subbasins of the middle reach of the Yellow River. The average annual runoff decreased significantly in the two subbasins and abrupt changes in the streamflow occurred during 1997. The average annual runoff in the Xiliugou and Hantaichuan basins decreased by 33% and 41%, respectively, from the period I to the period II. Two independent assessment methods consistently showed that the human activities are the primary drivers for the runoff reduction in the study area. Climate change was responsible for 22–32% of the streamflow reduction in the Ten Great Gullies Basin, whereas human activities were responsible for 68–78%. Among the various human activities, soil conservation measures such as returning cultivated land to forest or grassland and the construction of check dams had the most significant effects on streamflow reductions.

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## REFERENCES

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. FAO, Rome 300, 6541.

Bai, P., Liu, X.M, Zhang, D., Liu, C.M. 2020. Estimation of the Budyko model parameter for small basins in China. Hydrological Processes, 34, 125–138.

Bai, P., Liu, X.M., Liang, K., Liu, C.M., 2015. Comparison of performance of twelve monthly water balance models in different climatic catchments of China. Journal of Hydrology, 529, 1030–1040.

Bao, Z., Zhang, J., Wang, G. Fu, G., He, R., Yan, X.L., Jin, J.L., Liu, Y.L., Zhang, A.j., 2012. Attribution for decreasing streamflow of the Haihe River basin, northern China: Climate variability or human activities? Journal of Hydrology, 460–461, 117–129.

Birsan, M.V., Molnar, P., Burlando, P., Pfaundler, M., 2005. Streamflow trends in Switzerland. Journal of Hydrology, 314, 1–4, 312–329.

Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W., Vertessy, R.A., 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology, 310, 1–4, 28–61.

Budyko, M.I., 1974. Climate and Life. Academic Press.

Campbell, J.L., Driscoll, C.T., Pourmokhtarian, A., Hayhoe, K., 2011. Streamflow responses to past and projected future changes in climate at the Hubbard Brook Experimental Forest, New Hampshire, United States. Water Resources Research, 47, 2.

Chang, J.X., Wang, Y.M., Istanbulluoglu, E., Bai, T., Huang, Q., Yang, D.W., Huang, S.Z., 2015. Impact of climate change and human activities on runoff in the Weihe River Basin, China. Quaternary International, 380, 169–179.

Chen, Z.S., Chen, Y., Li, B.F., 2012. Quantifying the effects of climate variability and human activities on runoff for Kaidu River Basin in arid region of northwest China. Theoretical and Applied Climatology, 111, 3–4, 537–545.

Chu, J., Zhang, C., Wang, Y., Zhou, H., Shoemaker, C. A., 2012. A watershed rainfall data recovery approach with application to distributed hydrological models. Hydrological Processes, 26, 13, 1937–1948.

Dooge, J., Bruen, M., Parmentier, B., 1999. A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation. Advances in Water Resources, 23, 2, 153–163.

Feng, G.H., Zhang, Q.Q., 2008. Integrated management of ten major streams and floods safely passing through Inner Mongolia section of the Yellow River. Soil and Water Conservation in China, 4, 8–10.

Gao, G.Y., Fu, B.J., Wang, S., Liang, W., Jiang, X.H., 2016. Determining the hydrological responses to climate variability and land use/cover change in the Loess Plateau with the Budyko framework. Science of the Total Environment, 557, 331–342.

Guan, Y.B., Yang, S.T., Zhou, X., Liu, X.L., Chen, K., Wang, Z.W., 2016. Study on shrubs-herbs-arbor vegetation coverage and dynamic changes in the ten tributaries of Yellow River in Inner Mongolia by remote sensing method. Journal of Beijing Normal University, 52, 4, 458–465.

Hirsch, R.M., Slack, J.R., 1984. A Nonparametric Trend Test for Seasonal Data with Serial Dependence. Water Resources Research, 20, 6, 727–732.

Huang, S.Z., Chang, J.X., Huang, Q., Chen, Y.T., Leng, G.Y., 2016. Quantifying the relative contribution of climate and human impacts on runoff change based on the Budyko hypothesis and SVM model. Water Resources Management, 30, 7, 2377–2390.

Kendall, M., 1975. Rank Correlation Measures. Charles Griffin, London.

Lakshmi, V., Hong, S., Small, E.E., Chen, F., 2011. The influence of the land surface on hydrometeorology and ecology: new advances from modeling and satellite remote sensing. Hydrology Research, 42, 2–3, 95–112.

Li, L.J., Zhang, L., Wang, H., Wang, J., Yang, J.W., Jiang, D.J., Li, J.Y., Qin, D.Y., 2007. Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China. Hydrological Processes, 21, 25, 3485–3491.

Li, S., Xiong, L.H., Wan, M., 2011. Comparison of monthly water balance models. Journal of China Hydrology, 35, 5, 35–41.

Li, S., Xiong, L., Li, H.Y., Leung, L.R., Demissie, Y., 2016. Attributing runoff changes to climate variability and human activities: uncertainty analysis using four monthly water balance models. Stochastic Environmental Research and Risk Assessment, 30, 1, 251–269.

Li, Y.S., Si, B.L.G., Ma, Q.M., Wang, H.B., Jia, X.P., 2019. Erosion Sediment Yield Characteristics of Storm-floods in the Ephemeral Desert Watershed. Journal of Desert Research, 39, 2, 96–104.

Liang, K., Liu, C.M., Liu, X.M., Song, X.F., 2013. Impacts of climate variability and human activity on streamflow decrease in a sediment concentrated region in the Middle Yellow River. Stochastic Environmental Research and Risk Assessment, 27, 7, 1741–1749.

Liang, W., Bai, D., Jin, Z., You, Y.C., Li, J.X., Yang, Y.T., 2015. A study on the streamflow change and its relationship with climate change and ecological restoration measures in a sediment concentrated region in the Loess Plateau, China. Water Resources Management, 29, 11, 4045–4060.

Liu, Q., Yang, Z.F., Cui, B.S., Sun, T., 2009. Temporal trends of hydro-climatic variables and runoff response to climatic variability and vegetation changes in the Yiluo River basin, China. Hydrological Processes, 23, 21, 3030–3039.

Ma, H., Yang, D., Tan, S. K., Gao, B., Hu, Q., 2010. Impact of climate variability and human activity on streamflow decrease in the Miyun Reservoir catchment. Journal of Hydrology, 389, 3, 317–324.

Ma, X., Xu, J.C., Luo, Y., Aggarwal, S.P., Li, J.T., 2009. Response of hydrological processes to land-cover and climate changes in Kejie watershed, south-west China. Hydrological Processes, 23, 8, 1179–1191.

Masih, I., Maskey, S., Uhlenbrook, S., Smakhtin, V., 2011. Assessing the impact of areal precipitation input on streamflow simulations using the SWAT model. JAWRA Journal of the American Water Resources Association, 47, 1, 179–195.

Milly, P., Dunne, K., 2002. Macroscale water fluxes 2. Water and energy supply control of their interannual variability. Water Resources Research, 38, 10, 1206.

Modarres, R., Sarhadi, A., 2009. Rainfall trends analysis of Iran in the last half of the twentieth century. Journal of Geophysical Research-Atmospheres, 114, D3.

Mwangi, H.M., Julich, S., Patil, S.D., McDonald, M.A., Feger, K.H., 2016. Relative contribution of land use change and climate variability on discharge of upper Mara River, Kenya. Journal of Hydrology: Regional Studies, 5, 244–260.

Nagy, R.C., Lockaby, B.G., Kalin, L., Anderson, C., 2012. Effects of urbanization on stream hydrology and water quality: the Florida Gulf Coast. Hydrological Processes, 26, 13, 2019–2030.

Nash, J.E., Sutcliffe, J., 1970. River flow forecasting through conceptual models part I – A discussion of principles. Journal of Hydrology, 10, 3, 282–290.

Obeysekera, J., Irizarry, M., Park, J., Barnes, J., Dessalegne, T., 2011. Climate change and its implications for water resources management in south Florida. Stochastic Environmental Research and Risk Assessment, 25, 4, 495–516.

Pekarova, P., Miklanek, P., Pekar, J., Demuth, S., Gustard, A., Planos, E., 2006. Long-term trends and runoff fluctuations of European rivers. IAHS Publication, 308, 520.

Pettitt, A.N., 1979. A non-parametric approach to the change-point problem. Journal of the Royal Statistical Society, Series C (Applied Statistics), 28, 2, 126–135.

Ran, D.C., Zhang, D., D, F.F., Zhang, P., Jiao, P., 2015. Characteristics of the recent change of relationship between runoff and sediment in Xiliugou watershed. Yellow River, 37, 12, 1–4.

Roderick, M.L., Farquhar, G.D., 2011. A simple framework for relating variations in runoff to variations in climatic conditions and catchment properties. Water Resources Research, 47, 12.

Roudier, P., Ducharne, A., Feyen, L., 2014. Climate change impacts on runoff in West Africa: a review. Hydrology and Earth System Sciences, 18, 2789–2801.

Schaake, J.C., Waggoner, P.E., 1990. From climate to flow. In: Waggoner, P.E. (Ed.): Climate Change and US Water Resources. John Wiley, pp. 177–206.

She, D.L., Liu, D.D., Xia, Y.Q., Shao, M.A., 2014. Modeling effects of land use and vegetation density on soil water dynamics: implications on water resource management. Water Resources Management, 28, 7, 2063–2076.

Shope, C.L., Maharjan, G.R., 2015. Modeling spatiotemporal precipitation: effects of density, interpolation, and land use distribution. Advances in Meteorology, Article ID: 174196. DOI: 10.1155/2015/174196

Sun, Y., Tian, F.Q., Yang, L., Hu, H.P., 2014. Exploring the spatial variability of contributions from climate variation and change in catchment properties to streamflow decrease in a mesoscale basin by three different methods. Journal of Hydrology, 508, 170–180.

Wang, D., Hagen, S.C., Alizad, K., 2013. Climate change impact and uncertainty analysis of extreme rainfall events in the Apalachicola River basin, Florida. Journal of Hydrology, 480, 125–135.

Wang, D., Hejazi, M., 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. Water Resources Research, 47, 10.

Wang, E.L., Zhang, Y.Q., Luo, J.M., Chiew, F.H.S., Wang, Q.J., 2011. Monthly and seasonal streamflow forecasts using rainfall-runoff modeling and historical weather data. Water Resources Research, 47, 5.

Wang, S.J., Yan, Y.X., Yan, M., Zhao, X.K., 2012. Contributions of precipitation and human activities to the runoff change of the Huangfuchuan drainage basin: application of comparative method of the slope changing ratio of cumulative quantity. Acta Geographica Sinica, 67, 3, 388–397.

Xu, X.Y., Yang, H.B., Yang, D.W., Ma, H., 2013. Assessing the impacts of climate variability and human activities on annual runoff in the Luan River basin, China. Hydrology Research, 44, 5, 940–952.

Xu, X.Z., Zhang, H.W., Zhang, O.Y., 2004. Development of check-dam systems in gullies on the Loess Plateau, China. Environmental Science and Policy, 7, 2, 79–86.

Ye, X.C., Zhang, Q., Liu, J., Li, X.H., Xu, C.Y., 2013. Distinguishing the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment, China. Journal of Hydrology, 494, 83–95.

Zeng, Q., Chen, H., Xu C.Y., Jie, M.X., Chen, J., Guo, S.L., Liu, J., 2018. The effect of rain gauge density and distribution on runoff simulation using a lumped hydrological modelling approach. Journal of Hydrology, 563, 106–122.

Zhang, A.J., Zhang, C., Fu, G.B., Wang, B.D., Bao, Z.X., Zheng, H.X., 2012. Assessments of impacts of climate change and human activities on runoff with SWAT for the Huifa River Basin, Northeast China. Water Resources Management, 26, 8, 2199–2217.

Zhang, B.Q., Wu, P.T, Zhao, X.N., Wang, Y.B., Gao, X.D., 2013. Changes in vegetation condition in areas with different gradients (1980–2010) on the Loess Plateau, China. Environmental Earth Sciences, 68, 8, 2427–2438.

Zhang, C.Q., Zhang, B., Li, W.H., Liu, M.C., 2014. Response of streamflow to climate change and human activity in Xitiaoxi river basin in China. Hydrological Processes, 28, 1, 43–50.

Zhang, J.Y., Wang, G.Q., 2007. Study on the Impact of Climatic Change on Hydrology and Water Resources. Science Press, Beijing, China. (In Chinese.)

Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research, 37, 3, 701–708.

Zhang, L., Hickel, K., Shao, Q. 2017. Predicting afforestation impacts on monthly streamflow using the DWBM model. Ecohydrology, 10, 2, e1821.

Zhang, Q., Liu, J.Y., Singh, V. P., Gu, X.H., Chen, X.H., 2016. Evaluation of impacts of climate change and human activities on streamflow in the Poyang Lake basin, China. Hydrological Processes, 30, 14, 2562–2576.

Zhao, G.J., Li, E.H., Mu, X.M., Wen, Z.M., Rayburg, S., Tian, P., 2015. Changing trends and regime shift of streamflow in the Yellow River basin. Stochastic Environmental Research and Risk Assessment, 29, 5, 1331–1343.

Zhao, G.J., Mu, X.M., Strehmel, A., Tian, P., 2014. Temporal Variation of Streamflow, Sediment Load and Their Relationship in the Yellow River Basin, China. Plos One, 9, 3, e91048.

Zhao, H., Yang, S., Yang, B., Huang, Y. 2017. Quantifying anthropogenic and climatic impacts on sediment load in the sediment-rich region of the Chinese Loess Plateau by coupling a hydrological model and ANN. Stochastic Environmental Research and Risk Assessment, 31, 8, 2057–2073.

Zhao, X., Wang, G., Han, X.S., 2001. Harmfulness of ten big gullies in Inner Mongolia and corresponding treatments. Soil and Water Conservation in China, 3, 4–6.

Zhao, X.N., Zhang, B.Q., Wu, P.T., 2014. Changes in key driving forces of soil erosion in the Middle Yellow River Basin: vegetation and climate. Natural Hazards, 70, 1, 957–968.

Zhao, Y.F., Zou, X.Q., Gao, J.H., Xu, X.W.H., Wang, C.L., Tang, D.H., Wang, T., Wu, X.W., 2015. Quantifying the anthropogenic and climatic contributions to changes in water discharge and sediment load into the sea: A case study of the Yangtze River, China. Science of the Total Environment, 536, 803–812.

Zheng, H.X., Zhang, L., Zhu, R.R., Liu, C.M., Sato, Y.S.B., Fukushima, Y.S.H.R., 2009. Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. Water Resources Research, 45, 7.

Zhou, Y.Y., Shi, C.X., Du, J., Fan, X.L., 2013. Characteristics and causes of changes in annual runoff of the Wuding River in 1956–2009. Environmental Earth Sciences, 69, 1, 225–234.

Zuo, D.P., Xu, Z.X., Wu, W., Zhao, J., Zhao, F.F., 2014. Identification of streamflow response to climate change and human activities in the Wei River Basin, China. Water Resources Management, 28, 3, 833–851.

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